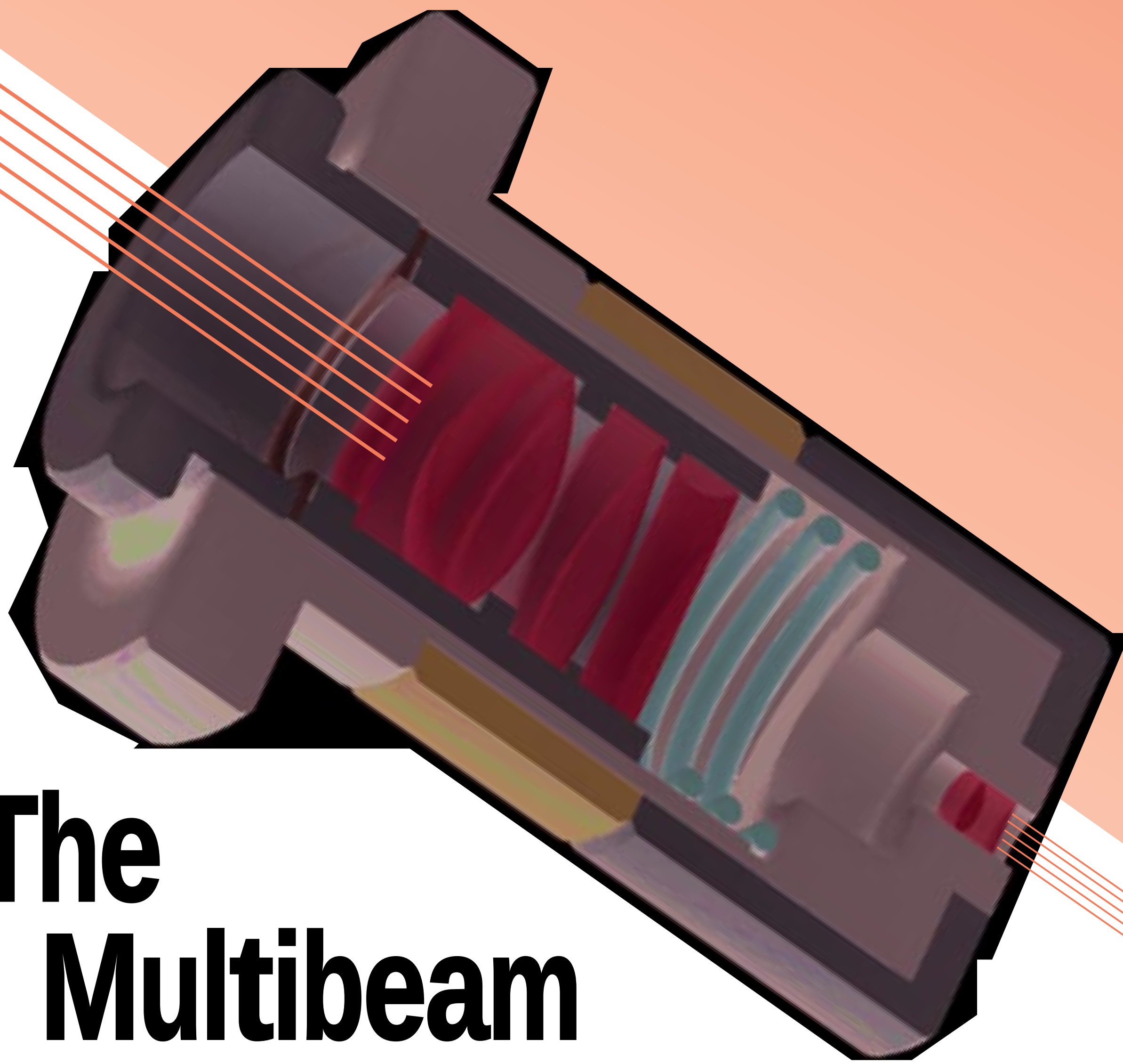


The Multibeam Fabry–Perot Velocimeter:

Efficient Measurement of High Velocities

Livermore scientists have designed a multibeam Fabry–Perot velocimeter that is proving invaluable to the Laboratory's science-based stockpile stewardship mission. It provides high-resolution, continuous data records about the behavior of weapons materials accelerated to velocities as high as 3,000 meters per second.

THE standard method for measuring speed that we all learned in school is to divide distance by time. If we measure velocity rather than just speed, we can obtain information on direction. But how do we measure velocities of as much as 3,000 meters per second over distances as short as 2 or 3 millimeters? And why would we want to take such measurements?

As part of our responsibilities for scientific stewardship of our nation's nuclear weapons stockpile, Lawrence Livermore National Laboratory performs a variety of experiments to study the velocity and other motions of materials accelerated by explosives, gas guns, and electrically accelerated plates. We use a number of diagnostic tools, including a Fabry–Perot velocimeter, to analyze these experiments. These experimental data are then used to certify the safety and reliability of our nuclear stockpile without the validation provided by underground tests.

In our studies, we seek information on the equations of state of various materials, the behavior of materials subjected to strong shock waves and other hydrodynamic phenomena, the explosion process, and the behavior of projectiles and targets upon and immediately after impact. For example, we may look at how materials respond to various hypothetical scenarios. Our ability to measure continually changing velocities is important because shock waves, for instance, cause objects to have velocities that are not constant—the object may accelerate, then decelerate, and then accelerate again, all within a few microseconds.

A typical experiment might involve testing the behavior of a high-explosive material that has been shaped into a disk and coated with a half-millimeter-thickness of copper. Several diagnostic tools would be used to study the high explosive, one being a Fabry–Perot velocimeter to measure the velocity of the copper after the high explosive is detonated from the back. Depending on the experiment, we have from only 1 to 100 millionths of a second to obtain information, from detonation to the point where dust and debris from the explosion get in the way of data collection.

We compare the results from tests such as these to the predictions from our hydrodynamic computer modeling codes to determine whether the codes make adequate predictions. If the codes do not match test results, such data as material strengths can be changed in the codes. In the absence of a nuclear test program, this validation process must continue until we have full confidence in our modeling codes.

Obtaining accurate measurements is thus of critical importance. But efficient use of budgeted funds is equally important. For example, we could do one experiment five times to collect five comparable data sets for validation purposes. But then we would have the cost of the experiment times five plus the problem of replicating the experiment precisely, which is extremely difficult. We might or might not in fact collect five comparable data sets from those five experiments (the perennial apples and oranges problem). It would be better to obtain all five data sets at the same time, saving time and money and ensuring that we are comparing apples with apples when we study the data. But a traditional Fabry–Perot system, one of the best instruments available for obtaining continuous data on high-speed velocities, was able to take only one or sometimes two sets of measurements at a time. We could use five velocimeters to obtain five simultaneous data sets, but their cost would be very high, and the equipment would take up much space and be difficult to maintain and operate.

Scientists at Lawrence Livermore's High Explosives Applications Facility have been working for over 15 years to improve our capability to gather accurate information about high velocities. Building on that experience, we recently combined several newly developed devices with a high-power laser, a Fabry–Perot interferometer, and five streak cameras to create a multibeam Fabry–Perot velocimeter (Figure 1). We have split the laser light into five individual beams with very high efficiency and have devised the technology for keeping the five light beams distinct. Collecting five data sets simultaneously from a single experiment using one interferometer is now a reality.

Single-Beam Velocimetry

For many years Lawrence Livermore National Laboratory has been using laser interferometry to make high-speed velocity measurements. Interferometry operates on the principle of the Doppler effect, which is the apparent difference between the frequency at which sound or light waves leave a source and the frequency at which they reach an observer, caused by the relative motion of the observer and the wave source. It is the Doppler effect that causes the apparent pitch of a passing train to rise as the train approaches (creating shorter wavelengths or higher frequency) and to drop as the train moves away (creating longer wavelengths or lower frequency).

This same principle may be applied to the experiment described on p.13.

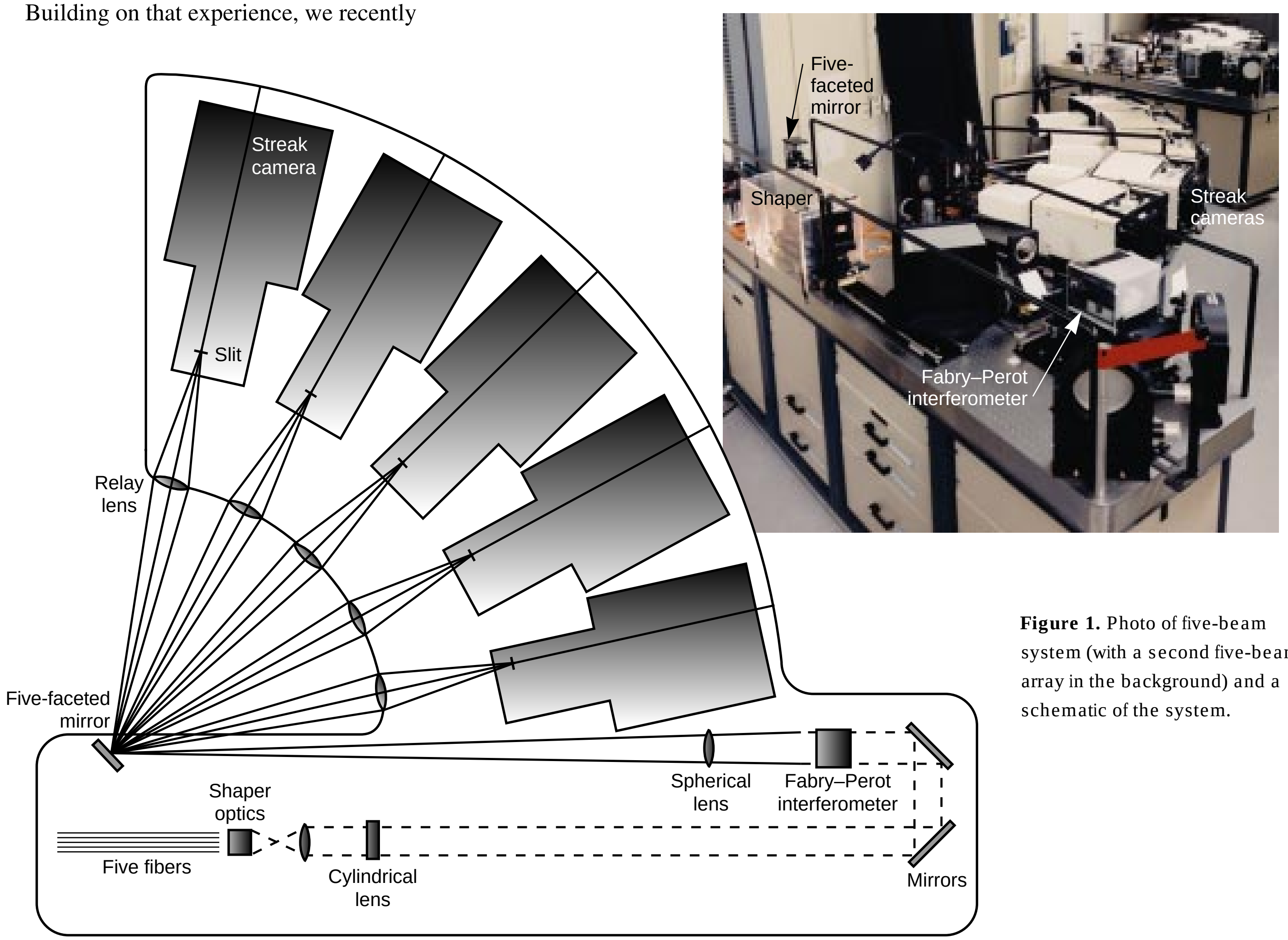


Figure 1. Photo of five-beam system (with a second five-beam array in the background) and a schematic of the system.

We can shine laser light on the copper as it is being accelerated toward the light and collect some of the light that reflects off the copper. The velocity of the copper as it accelerates but before it disintegrates after detonation can be inferred by measuring the slight changes in the wavelength of the reflected light as the copper moves toward the unmoving light source. Because light waves are so small (about 2,000 wavelengths per millimeter), using them as a measuring device provides extremely high sensitivity. The laser's frequency is 6×10^{14}, or 600 trillion oscillations per second. Fifteen billion oscillations will occur in an experiment as brief as 25 microseconds.

The reflected light is sent through an interferometer, which splits the light source into several beams, sends them along different paths, and then combines them in an "interference" pattern. (In physics, interference refers to the increased amplitude of a wave that results from superimposing two or more waves of the same or nearly the same frequency.) Very precise velocity measurements may be made from this interference pattern.

The Fabry–Perot interferometer is almost 100 years old. Today, the Laboratory's version consists of a pair of round slabs of special glass, about 2 centimeters thick and about 7 centimeters or more in diameter. They are ground and polished flat to approximately one two-hundredth of a wavelength of light (or about three-millionths of a millimeter). The glass is made highly reflective by about 20 coatings of dielectric material evaporated onto its surface. The separation between these precisely parallel mirrors depends on the demands of the particular experiment and can range from a few millimeters for some applications to as much as 15 centimeters.

Before entering the Fabry–Perot, the reflected light passes through a cylindrical lens (see Figure 2), which converges the light vertically while maintaining the beam's horizontal dimension. Concentrating the light in this manner results in more usable light inside the interferometer.

The Fabry–Perot's first mirror is almost perfectly reflective (99.5%) and has a 0.75-millimeter-wide stripe of the dielectric coating removed from across its middle. The second mirror is typically about 93% reflective. Light enters the Fabry–Perot through the stripe in the first mirror and bounces back and forth between the mirrors about 50 to 100 times, creating the same number of weak transmitted beamlets parallel to each other and staggered in time. Because of the almost perfect reflectivity of the first mirror, virtually no light is lost back out the front mirror, except for a small amount that goes back through the stripe. The reduced reflectivity of the second mirror allows the beamlets to pass through it.

Each set of 50 to 100 beamlets travels a path from the first mirror, through the second mirror, and through a spherical lens to that lens's focal plane. Figure 2 shows that the first of the beamlets travels the shortest path, the second bounces once on the striped mirror before passing through the second mirror, the third bounces twice, etc. If the difference in the lengths of the paths of the successive beamlets is an integer number of wavelengths (e.g., 10,002 or 300,000), then the beamlets are all in phase and will interfere with (that is, reinforce) each other when they reach the spherical lens's focal plane. The

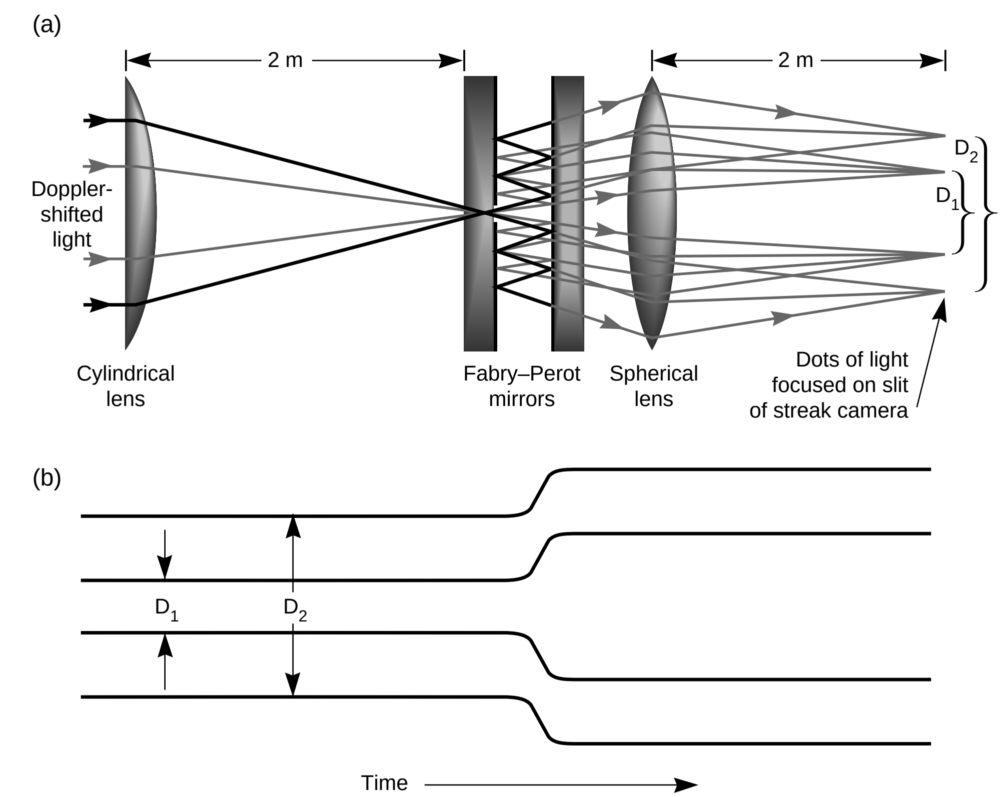


Figure 2. (a) A top view of the Fabry–Perot velocimeter system from the cylindrical lens to the slit in the streak camera. The interference pattern of bright dots—D_1 and D_2—is recorded on the streak camera. (b) A hypothetical streak camera record shows what happens to D_1 and D_2 when acceleration occurs. Velocities are determined using a formula based on measurements of the separation between the dots.

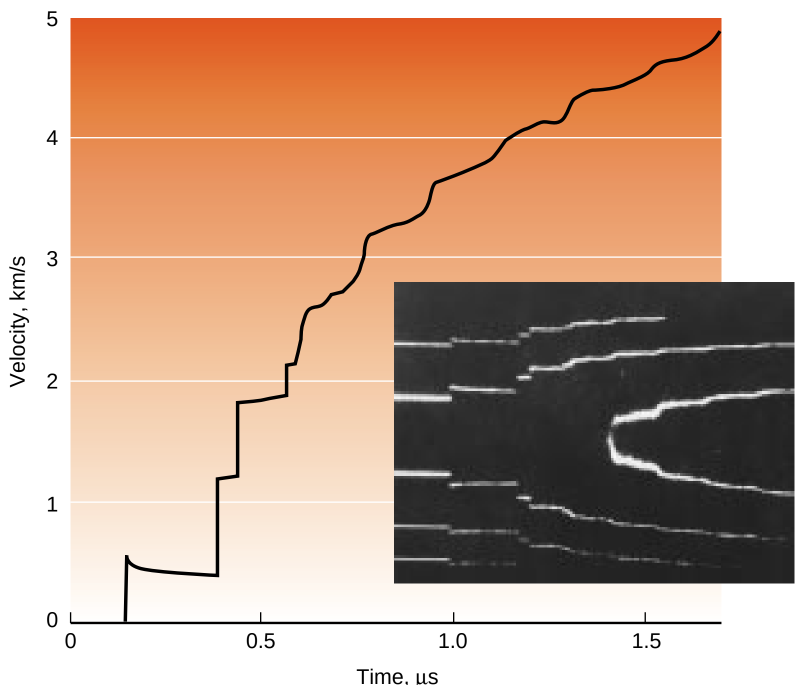


Figure 3. A time sweep as recorded by a streak camera (inset) translates into the velocity vs time record shown on the graph.

interference pattern of each set of beamlets creates a bright dot.

Only certain combinations of the reflected light's wavelength and angle of reflection and the distance between the Fabry–Perot mirrors create resonant angles, which cause the beamlets from a given beam to have the same phase and to interfere constructively with one another. The combination of the cylindrical lens and the narrow stripe in the first mirror assures that virtually all of the light entering the Fabry–Perot is at vertical angles, creating enough resonant angles to create six or eight bright dots.

As the copper accelerates, the reflected light's wavelength decreases, the resonant angles therefore increase, and the separation between the bright dots increases. This image of dots, known as an interference fringe, enters an electronic streak camera through a narrow vertical slit. In the streak camera, the image is swept across a piece of film (see Figure 3).

From the width and number of the fringes, extremely sensitive measurements can be made of the velocity history of the copper as a function of time, starting before acceleration began and continuing as long as conditions permit. The record of velocity versus time can be inferred using a formula that is based on measurements of the separation between the dots. Simple measurements of dot separation can be done with a magnifier and scale, and more precise analysis is done by digitizing the record.

Our Multibeam System

To collect five simultaneous sets of data, we cannot simply run five beams through a Fabry–Perot interferometer. Whereas the one-beam output is a series of bright dots with high velocity resolution, five beams would produce smeared records with low resolution. To obtain the high resolution required for precise velocity measurements, special optics are required to shape the five beams and keep them distinct.

There also needs to be a good way to split the laser light into five beams and to get the five reflected beams back to the instrumentation. The old method of shining the laser beam through a tilted mirror with a small hole in it works for one beam but would be unwieldy for more. There is also the problem of directing multiple outputs from the Fabry–Perot interferometer to several streak cameras.

The Laser

We use a frequency-doubled, neodymium-doped yttrium–aluminum–garnet (Nd:YAG) laser that produces a very pure green light for 80 microseconds. "Pure" color means that there is no change in the light's wavelength or frequency even over a distance of more than 10 meters and that the frequency is stable to 50 parts per billion for the duration of the experiment. Precise velocity measurements require that the light remain in phase across a distance equal to the total number of roundtrip "bounces" between the Fabry–Perot mirrors, or 5 to 20 meters depending on the separation between the mirrors.

A beam splitter divides the laser beam into five individual beams, which are carried to the experiment on fiber-optic lines. We have designed special probes, each of which holds two fiber-optic lines—one to carry light to the experiment and another to carry reflected light back to the instrumentation.

Figure 4 is a series of photographs of the experiment described on p. 13. The five beams are visible as the disk begins to explode.

Keeping Five Beams Separate

As the 1- to 100-microsecond experiment takes place, the reflected light travels into the instrument room and through the "shaper," which is the heart of our multibeam system. The shaper is a complex of lenses of Laboratory design that compresses the fiber images horizontally by a factor of 4 (from 100 micrometers to 25 micrometers) while maintaining the vertical dimension of 100 micrometers (see Figure 5). Even with this compression, we can preserve the same angular divergence of the light at the image as it had at the experiment. Now the five sets of dots are well separated relative to their width, and no light that could be used is wasted. (In single-beam as well as multibeam velocimetry, some light is wasted because the light comes in on a larger fiber than the instrumentation can use.) The shaper sends the light from the separate fibers into the velocimeter at slightly different horizontal angles, so that any given horizontal angle corresponds to only one fiber. The five beams can thus be distinguished from one another later when the streak camera results are analyzed.

The shaper can actually handle ten beams, although to date it has handled just five because of space limitations for streak cameras.

Getting Beams to Cameras

Our five-beam system creates five columns of six to eight bright dots. The columns, each of which comes from a specific incoming fiber, are only 0.9 millimeters apart horizontally at the focal plane of our spherical lens. We have designed and constructed a five-faceted mirror about 3 centimeters high, with the center of the three middle facets just 0.9 millimeters apart. The five facets are separated in angle by 7.5 degrees, allowing the five streak cameras to be placed 15 degrees apart. Each streak camera views one column of the faceted mirror through a large relay lens.

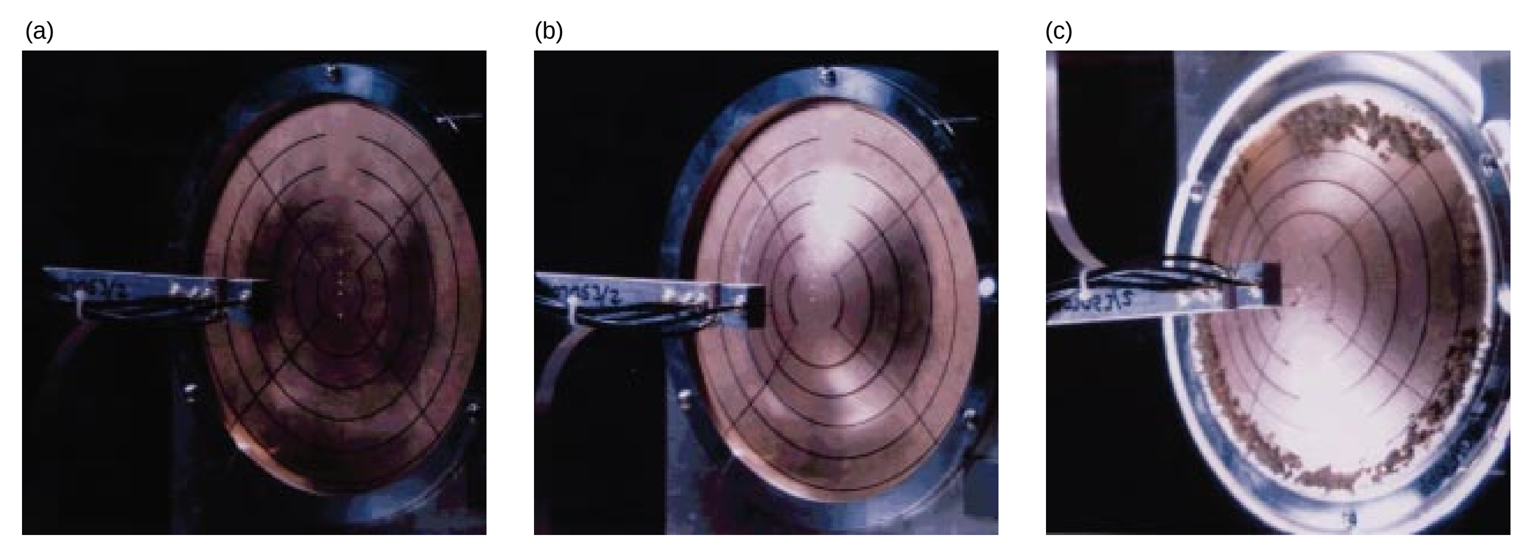
"Foolproofing" the System

Our work on the Fabry–Perot velocimeter system has not been limited to pushing five beams through a single interferometer. We have made other improvements that make it an even more useful diagnostic tool whose records are now virtually foolproof to analyze.

A Referee to Verify Results

When a shock wave arrives at an object, the object's velocity can increase very rapidly, often too fast for our system

Figure 4. In photos of the experiment described on p. 13, the five laser beams are visible on the copper, but the probes themselves are out of the field of view. The visible bracket holds timing pins that short out when the copper material hits them. That timing information tells scientists the shape of the experiment as it explodes. Photo (a) was taken before detonation and (b) was taken 8 microseconds after detonation as the shock waves have reached the fourth ring. In (c), taken 14 microseconds after detonation, the dark material near the edge is the copper coming apart. The white glow around the edge of the disk is gas from the high explosives.



to follow. Every time the velocity increases by a fixed amount (for example, by 0.6 millimeters per microsecond, a value that will vary depending on the distance between the Fabry–Perot mirrors), the dot pattern repeats itself. This means that if the increase is too rapid to follow continuously, not one but several possible velocities can be inferred. Often common sense and experience allow us to infer the correct velocity. But in unusual experiments, this easy inference is not possible, and we therefore devised the dual-cavity interferometer, which has two mirror distances within the same unit.

With some of the light inside the interferometer traveling one distance and some a smaller distance, we obtain two sets of interference fringes for each beam coming from the cylindrical lens. Each streak camera thus records two sets of fringes (see Figure 6). This second, "referee" set of fringes is a significant aid in resolving the uncertainty in reading rapid acceleration data. Analysis of the fringe overlap shows that there is always, at any velocity, an adequate set of separated fringes to correctly interpret the experimental data.

In our latest version of the dual-cavity interferometer, we create the second cavity by suspending a piece of very-high-quality glass, about 2.5 centimeters square and 7.5 centimeters high, between the Fabry–Perot mirrors. It is relatively inexpensive and can be inserted or removed as experimentation needs demand.

Customized Streak Cameras

A relay lens images the dots from the faceted mirror to the vertical slit of the streak camera, which sweeps and intensifies the image across a piece of film, providing the record of velocity versus time. The electronics and housings for the cameras were custom made at the Laboratory to obtain special features not available commercially. For example, our cameras can be made to sweep the dot image at one speed for part of the record and then at another speed during the remainder of the record. This feature allows better time resolution for particular parts of the record. We have also installed a special time fiducial system, which provides both bright and dim marks in the field of view to allow absolute timing references between cameras.

Using the Incoming Beam Twice

For some experiments, we want the streak cameras to operate at very fast sweep rates to obtain fine velocity details but also to sweep more slowly to record the entire motion. With the dual sweep-speed streak cameras described above, we can do this using as many beams as there are cameras. However, by using ten cameras for five beams, we can get more detailed information.

We can have two cameras recording an experiment at two different speeds by making use of the fact that light comes into our multibeam system from a larger fiber size than the interferometer and streak cameras can use. After the reflected light goes through the shaper, the excess light enters a system of mirrors that carries it up, over, and down to another table set up with a second interferometer and five more streak cameras. This way, the first camera on the second table records slowly the same velocity history that the first camera on the first table is recording more rapidly. We have found that this method makes a far more efficient use of available light than a beam splitter would, and it has been successfully used on dynamic experiments.

The Power of Velocimetry

Fabry–Perot velocimetry provides unambiguous records of very complex situations. For example, in some experiments rather like the one described on p. 13, evaporated gold layers are applied to surfaces for higher reflectivity. After the shock wave arrives, the surface often decelerates, and sometimes part of the gold pulls away from the surface, a process known as spallation. If illumination by the probe covers areas of the surface where gold has spalled and areas where it has not, we get two different velocity histories on the same camera. There may also be unshifted (no change in wavelength) light from non-moving surfaces such as a vacuum window, dust, or uncoated glass, in addition to shifted light from moving surfaces. Fabry–Perot interferometry can handle all of these situations on a single, easily read record.

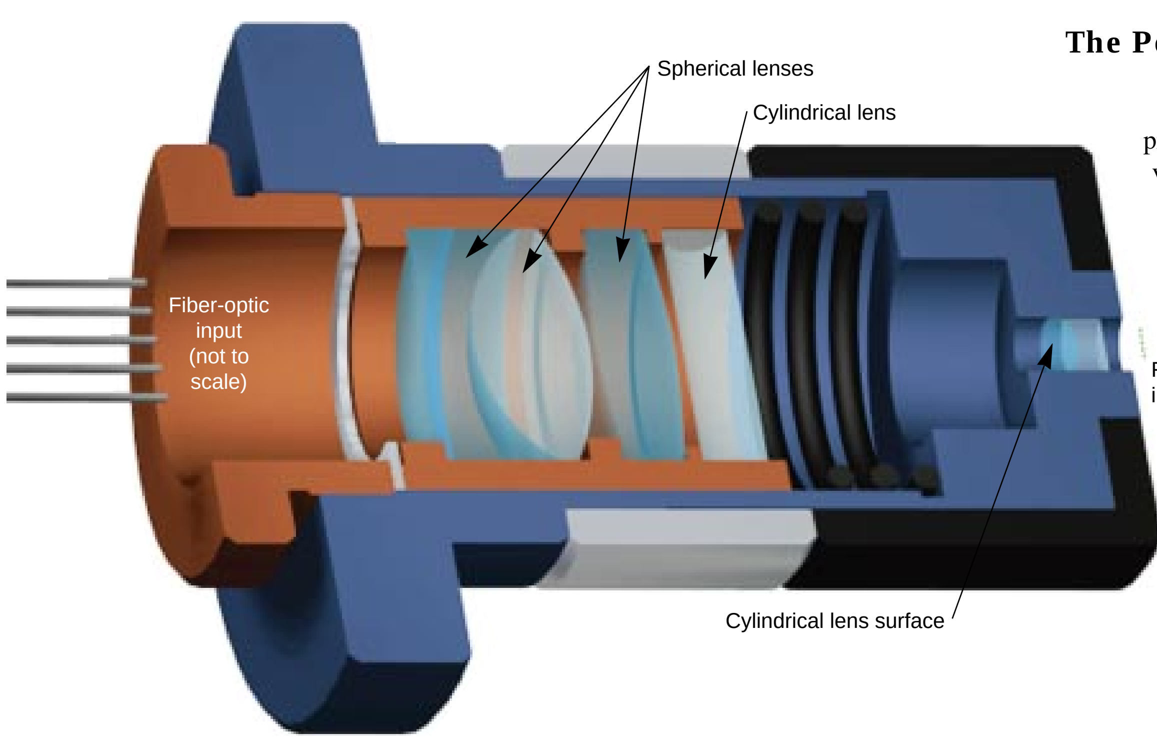


Figure 5. The shaper is the device that allows us to use five light beams simultaneously.

The Fabry–Perot velocimeter is unique in providing information on continuous velocity from both simple and complex experiments. The multibeam Fabry–Perot velocimetry system is a powerful, practical diagnostic tool whose results can be quickly and easily verified. The value of the multibeam system has been recognized beyond the boundaries of the Laboratory: two five-beam arrays will soon be installed at the Nevada Test Site for non-nuclear testing.

We presently have a ten-beam capability, with two five-beam arrays. We are in the process of expanding to four five-beam arrays, which will give us 20 simultaneous sets of measurements, at approximately half the cost of 20 single-beam Fabry–Perot velocimeters. As the system is further developed and expanded, it will become an ever more useful tool, with improved time and velocity precision.

With the multibeam system producing more meaningful data than has been available to us in the past, we can make our modeling codes increasingly accurate—a necessity for effective stewardship of our nuclear stockpile.

Key Words: Fabry–Perot interferometry, optical velocimetry, optics, streak cameras.

For further information, contact David Goosman (510) 422-1630.

(a)

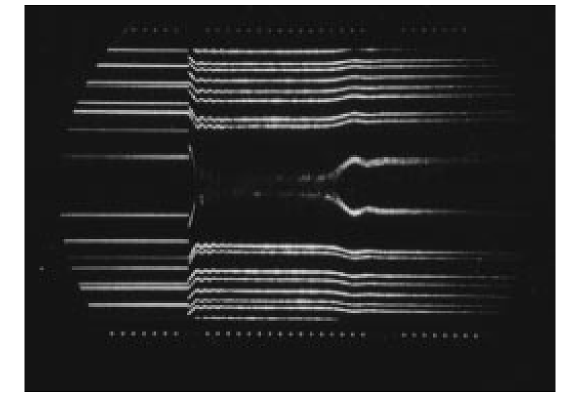
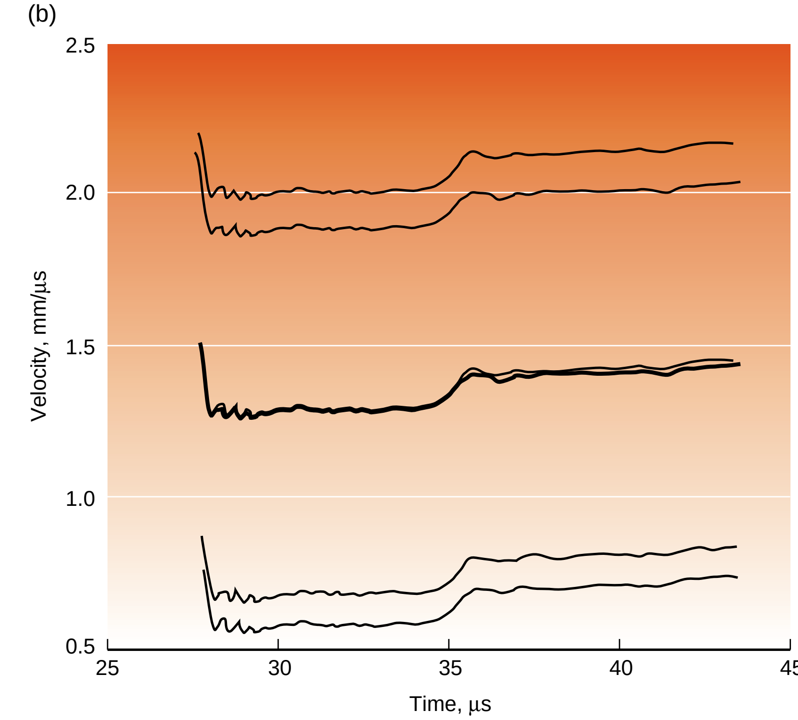


Figure 6. (a) An example of a streak camera record from an earlier version of our dual-cavity Fabry–Perot interferometer. (b) An example of data analysis using three different estimates of the "jump" in the dot pattern when rapid acceleration occurs. Without the second set of fringes, the scientists would not know which is correct. The overlap of the center two curves shows it to be the correctly estimated velocity.

(b)



About the Scientist

DAVID R. GOOSMAN joined the Laboratory in 1974 and has been Group Leader for Advanced Experiments Projects since 1980. He received a Ph.D. in Nuclear Physics from California Institute of Technology in 1967, and from 1967 to 1969, he was a post-doctoral fellow there. From 1969 to 1974, he carried out nuclear physics experiments at Brookhaven National Laboratory. He has published more than 60 articles on nuclear physics, radiography, and optical velocimetry.